Multi-Shell Plasma Flow Switch Experiments on the GIT-12 Generator[1]

V.A. Kokshenev, A.Yu. Labetsky, B.M. Kovalchuk, S.A. Chaikovsky, A.V. Fedunin,
F.I. Fursov, N.E. Kurmaev, A.G. Rousskikh, A.V. Shishlov*, N.A. Zhidkova

Institute of High Current Electronics SB RAS, 2/3 Academichesky ave., Tomsk, 634055, Russia,
phone: +7 (3822)- 492908, fax:+7 (3822)- 492751, e-mail: vak@oit.hcei.tsc.ru
**Faculty of Electrophysics and Electronic Equipment, Tomsk Polytechnic University,*
30 Lenin Ave., Tomsk, 634050, Russia

Abstract – In this paper, the experiments with a combined plasma flow switch coupled with a Z-pinch load are presented. An outer shell was formed by the plasma guns, the inner shells were gas puffs. It has been demonstrated that the use of the plasma outer shell allows stabilization of the motion of the plasma sheath and reduction of its thickness. The current rise rate of 10^{14} A/s was registered in the experiments with a Z-pinch load.

1. Introduction

Generation of high-power pulses of soft X-ray radiation requires formation of the current pulses in an imploding load in a time, which is less than the typical times of the instability development (≤100 ns). One of the ways to solve this problem (for the existing current generators) is the use of a megaampere load current multiplier [1] coupled with the plasma flow switch (PFS) for the sharpening of the current pulse of a microsecond generator. A promising scheme is a combined radial plasma flow switch [2], where the plasma flow movement and the corresponding switching power are directed towards the load. In such configuration, the load inductance can be minimized up to 5 nH. More than 90% of the generator current can be switched in the load in a time less than 100 ns at the PFS impedance ~0.1 Ohm.

The experiments in the microsecond implosion regime at the current levels of 10 MA require the use of large initial diameter loads. However, the plasma pinch quality deteriorates drastically with the increase in the initial shell radius because of the instability development. Therefore, the single-shell Z-pinches have very low efficiency as plasma radiation sources.

In [3], we have shown the principal possibility of formation of 1-mm-diameter tight pinch for the case of implosion of a triple-shell gas puff with the initial radius of 160 mm. The investigation of mechanisms of energy transfer into the pinch plasma is of great interest. Despite the fact that the experimental results [3] qualitatively confirm the efficiency of plasma stabilization by the snowplow mechanism, the supposition of the plasma-dynamic switching of the current into the middle and inner shells was made. The outer shell operates as a plasma-dynamic switch. During the implosion of this shell, the light plasma sheath is formed due to the development of large-scale instabilities. In this case the energy is delivered to the plasma of the middle and inner shells due to the hydrodynamic plasma flows and the magnetic field penetration. The rate of magnetic field penetration (i.e. the current sheath velocity) can be up to 10^8 cm/s. The concept of using of the outer gas shells for the sharpening of the load current rise times was experimentally examined in [2].

Non-diffusive convective penetration of the magnetic field (current) into the plasma sheath, which has azimuth density non-uniformities, can occur in the form of long thin streams [4]. A possible asymmetry of the gas puff breakdown because of nonuniform ionization of the gas puff at the initial stage of current sheath formation can be a cause of the density non-uniformormity development. In the experiments [2, 3], the gas puff preionization was done by flashboards. Four flashboards with four discharge channels on each were placed symmetrically around the circle at the distance of 24 cm from the pinch axis. The flashboards were triggered 1 μs prior to the onset of the load current. This can lead to the situation when a part of the imploding matter falls out the implosion process and stays behind the current sheath. This residual matter is capable of shunting the significant portion of the current when the inductive voltage $U \sim I \cdot dL/dt$ grows. The calculations show that this voltage at the entrance of the radial line reaches several hundreds of kilovolts. Another important factor is the process of the current sheath broadening. It can be connected with the presence of the conducting matter behind the current sheath, for example, due to ionization of the residual gas, or diffusion of current sheath into the region with falling gas density. These processes limit the load current sharpening.

At the initial stage of the implosion of multi-shell load, a symmetrical large-diameter current sheath can

---

[1] The work was supported by RFBR Grant # 05-02-16662.

be formed by using the outer plasma shell. This approach is well known. In the Z-pinch experiments [5], the outer plasma shell was used for providing the breakdown symmetry and for prevention of the current shunting at the instant of the maximum plasma compression. The experiments with the radial multi-shell PFS with the plasma outer shell are presented.

2. Experimental setup and diagnostics

The experiments were carried out on the GIT-12 [6] pulsed current generator operated in microsecond implosion regime. In this regime, the generator provides the current of 4.7 MA with the current rise time of 1.6 μs in the short-circuit load. The scheme of the combined radial plasma flow switch coupled with the Z-pinch load is shown in Fig.1. The gas injection and the plasma injection were carried out from the anode. The plasma shell was formed with the help of 48 plasma guns distributed symmetrically at the diameter of 350 mm. The capillary-type plasma guns [7] allowed production of the heavily ionized plasma consisted of hydrogen (H^+) and carbon (C^+, C^{++}) ions. When the plasma guns were triggered (3 μs before the operation of the Marx generator), the plasma shell with a mass of ~20 μg/cm was formed in the PFS interelectrode gap.

Gas shells were produced by the pulsed gas injection with the help of the fast electromagnet gas valve coupled to concentric annular nozzles [8]. Neon was used as a working gas. The diameter of the outer gas shell was 240 mm; the diameter of the middle gas shell was 100 mm; the diameter of the inner solid fill gas shell was 20 mm. The transparent rib cathode was used.

The B-dot probes were used to monitor current in the plasma flow switch region and in the load region. The single-loop probes of 1-mm diameter were placed at the cathode-side between the shells at the distances of 7 cm and 3 cm from the axis. The accuracy of these current measurements is ~20%. The generator current *IG* was measured by the inductive ring located 100 mm upstream to the entrance of the radial line. The radial implosion dynamics was recorded by visible-light streak camera. The time-integrated pinhole camera produced the pinch image in the final stage of implosion in the spectral range of Ne *K*-lines. The K-shell radiation yield and power were measured by vacuum X-ray diodes (see Ref.2 and 3 for the details).

3. Experimental results and discussion

To analyze the results of the experiments with the combined PFS we use simple and direct method of comparison. In Fig.2, the typical traces of the current switching from the outer shell to the load for the 240-mm-diameter gas outer shell are shown (shots #766, #791). The corresponded current traces for the plasma outer shell of 350-mm diameter are shown in Fig.3 (shots #849-851). The outer shell was used as a driver of the current to the load region. In both cases, the load was a double-shell gas puff with the shell diameters of 100 mm and 20 mm and equal masses of the gas shells (~150 μg/cm). The use of the term "load" regarding to the middle shell is conditional, because it is a part of the plasma flow switch, but the absence of this shell deteriorates the radiation characteristics significantly.

As follows from the given current traces, at the same generator current (~3.7 MA), the current switching regimes are substantially different. The signals from the B-dot probes allow determining the dynamics of the current sheath formation and its quantitative characteristics. More compact sheath is realized in the PFS experiments with the plasma outer shell. The current rise rate reaches the value of 10^{14} A/s and the current rise time is 30 ns.

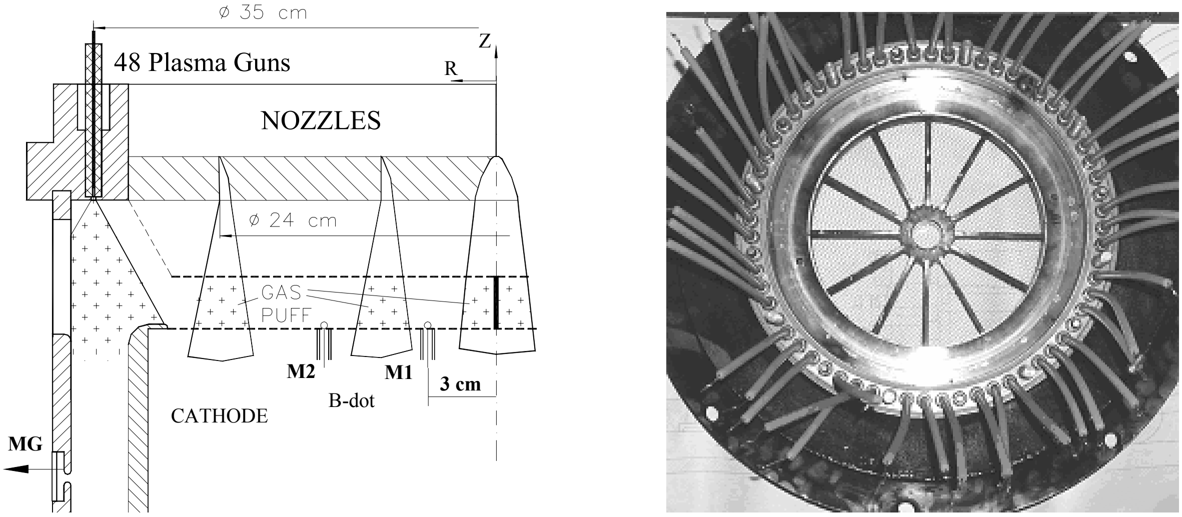

Fig. 1. The scheme of load unit with the PFS and the photo of the anode unit

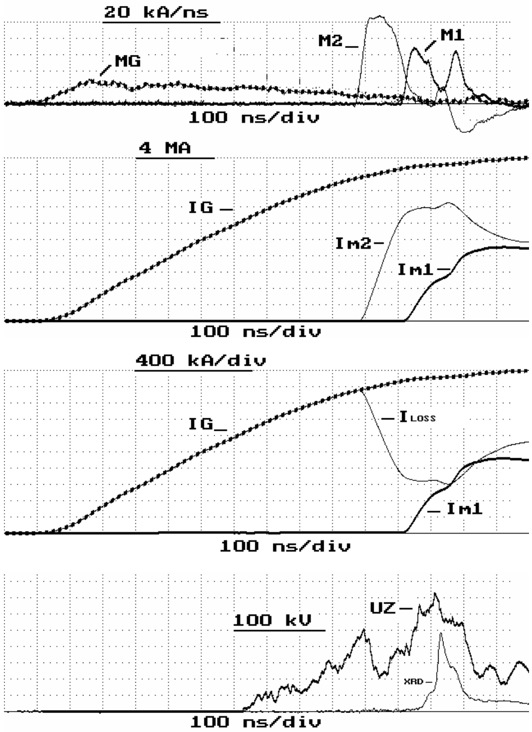

Fig. 2. Typical traces of the current switching from the outer shell to the load for the gas outer shell (#791)

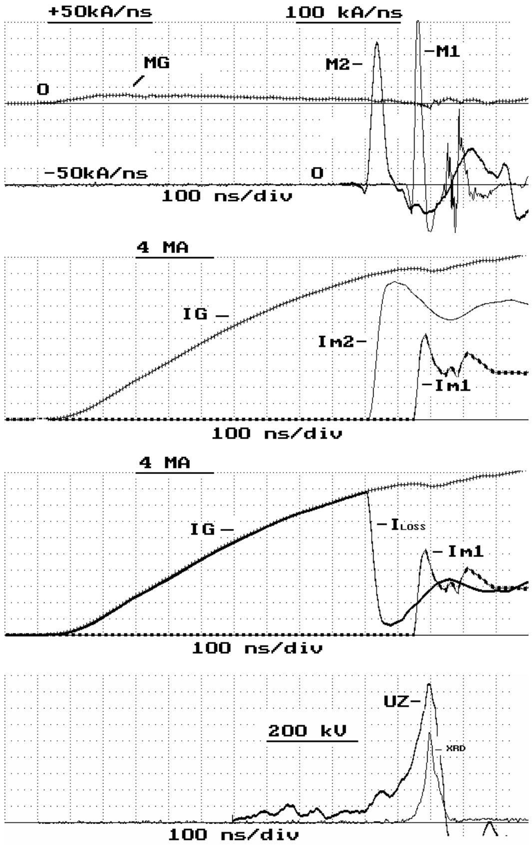

Fig. 3. Typical traces of the current switching from the outer shell to the load for the plasma outer shell (#849)

In the PFS experiments with the gas outer shell (#791), the current *Im*2 is no more than 70% of *IG* at the radius of 7 cm. At the radius of 3 cm, the current *Im*1 is about 50% of *Im*2 (i.e. ~30% of *IG*). The current sheath velocity derived from the B-dot measurements is ~$2.5 \cdot 10^7$ cm/s; the current sheath thickness is 2÷3 cm. The average current density j_z in the sheath is ~20 kA/cm^2.

In the case of the plasma outer shell (#849), the current *Im*2 is ~90% of *IG* at the radius of 7 cm. At the radius of 3 cm, the current *Im*1 is about 70% of *Im*2 (i.e. ~60% of *IG*). The velocity of the current sheath is ~$4 \cdot 10^7$ cm/s; the current sheath thickness is 1÷1.5 cm. The average current density in the sheath is ~40 kA/cm^2.

It is necessary to point out that in the experiments with the combined PFS the current losses during the motion of the current sheath were registered as well. The value of I_{LOSS} was determined as follows. It is a current that flows outside the radius of 7 cm: $I_{LOSS} = IG - Im2$. Though, for the plasma outer shell the current losses are noticeably smaller during most of the implosion time (~10% against 30%), they increase and become equal to that in the case of the gas outer shell at the instant of the maximum pinch compression (the XRD peaks in Fig.2 and 3). At the radius of 3 cm, the current losses reach the level of 50% for the plasma PFS and ~70% for the gas PFS. Very likely, it is connected with the grows of the voltage *UZ* in the radial line that leads to the increase of the conductivity in the regions behind the current sheath.

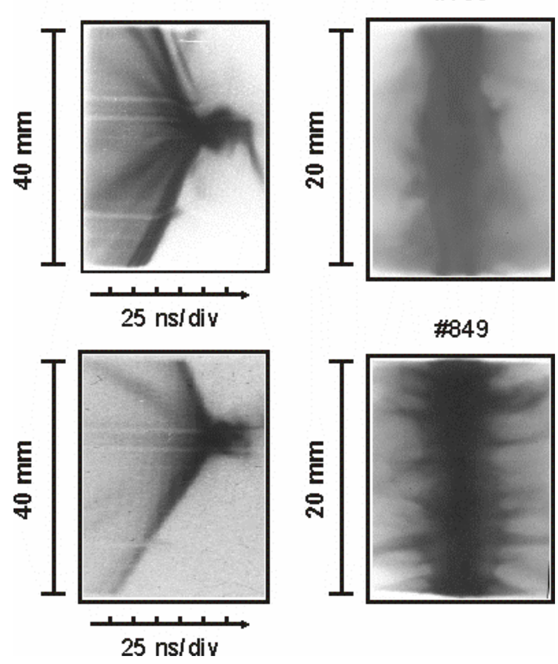

Fig. 4. Streak camera and pinhole camera pictures for the shots with the gas (#766) and plasma (#849) outer shells.

From the data mentioned above, the value of the Hall field in the current sheath can be estimated. Under the assumption that 10÷20% of plasma is ionized $E_r = j_z H_\varphi / enc$ ~ 10÷20 kV/cm. In such electric fields, the neon ions accelerated in front of the current sheath reach the energies of 10÷30 keV that corresponds to the velocities of $(3÷5)\cdot 10^7$ cm/s. It is sufficient for the efficient generation of the K-shell radiation. This result can be used (among the others) for the explanation of the fact that the XRD signal begins almost at the same instant with the current sheath arrival at the radius of 3 cm (see Fig.2 and 3). The presence of a prepulse of the reverse polarity on the B-dot signals (more pronounced for the plasma outer shell) may be related with the formation of the current precursor.

The positive tendency in the experiments with the plasma outer shell is confirmed by the optical and X-ray measurements. The streak camera pictures given in Fig.4 indicate that more uniform sheath is formed in the case of the plasma outer shell (#849) as compared to the gas outer shell (#766). At that, the tight pinch is observed in the pinhole camera picture.

As follows from the given data, the use of the plasma outer shell has a positive effect on formation of the compact current sheath. At the generator current amplitude of 4 MA and the current rise time of ~1 μs, the current switched to the imploding load was 2.2 MA, and the current rise time was 30 ns. To reduce the current losses and to achieve a higher X-ray radiation power, optimization of the load parameters and the geometry of the intermediate shells are required. It will be the subject of further investigations.

References

[1] V.A.Kokshenev, A.A.Kim, B.M.Kovalchuk *et al.*, “MA Load Current Multiplier”, presented at 14th Symposium on High Current Electronics, Tomsk Russia, 2006.

[2] S.A.Chaikovsky, V.A.Kokshenev, A.G.Rousskikh *et al.*, *in Proc. 13th Symposium on High Current Electronics*, 2004, pp.380-383.

[3] A.V.Shishlov, R.B.Baksht, S.A.Chaikovsky *et al.*, *in Proc. 13th Symposium on High Current Electronics*, 2004, pp.319-322.

[4] A.S.Kingsep, and L.I.Rudakov, Plasma Phys. Rep. (in Russian) **21**, 611 (1995).

[5] A.N.Mokeev, and V.V.Prut, Instr. Exp. Techniques (in Russian) **6**, 153 (1986).

[6] S.P.Bugaev, A.M.Volkov, A.A.Kim *et al.*, Russ. Phys. J. **40**, 38 (1997).

[7] V.A.Kokshenev, N.E.Kurmaev, and F.I.Fursov, *in Proc. 12th Symposium on High Current Electronics*, 2000, pp.268-273.

[8] R.B.Baksht, A.V.Fedunin, A.S.Chuvatin *et al.*, Instr. Exp. Techniques **41**, 536 (1998).